AMPLIFICATION AT LOW FREQUENCIES

LESSON NO. ND-15

SPRAYBERRY ACADEMY of RADIO

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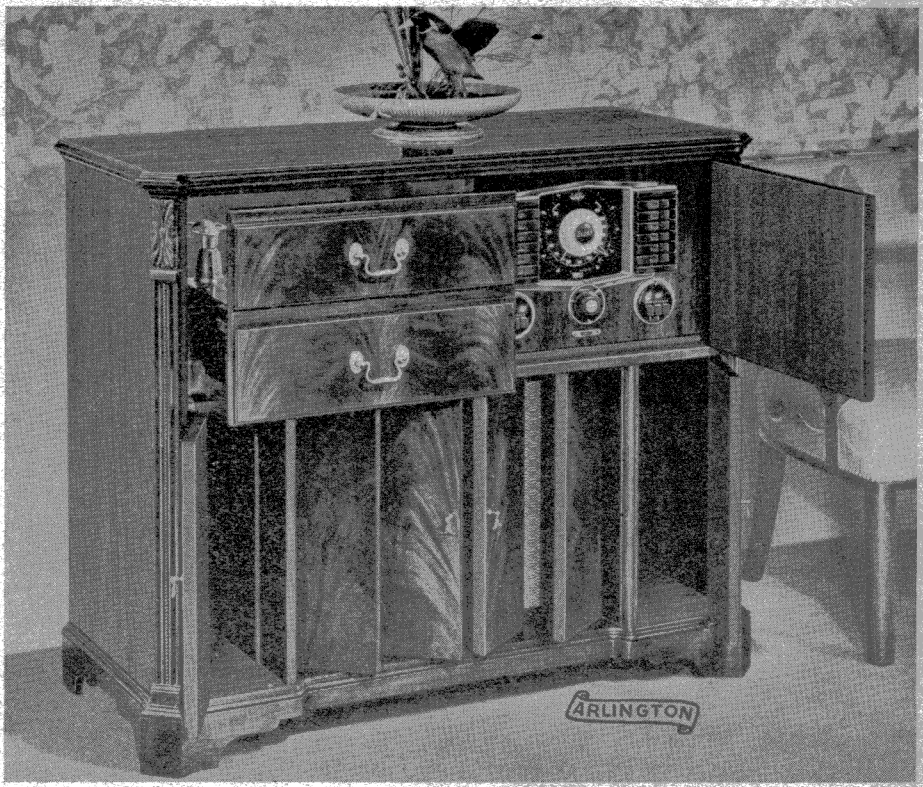


The above view shows the exterior of a modern *Zenith* receiver with a high quality audio amplification system. It includes facilities for record reproduction. Remember as you study this lesson reference is made to all radio sets such as the above.

AMPLIFICATION AT LOW FREQUENCIES

Lesson No. ND-15

Your study of amplification up to now has dealt mainly with high frequencies—that is, with *modulated* high frequency carrier waves as radiated by radio stations. This represents a low A.F. signal superimposed on a relatively high frequency which acts as a carrier frequency as mentioned in other lessons. Amplification of these frequencies is called R.F. or high frequency amplification. This is the type of amplification usually employed before the signal reaches the *detector or demodulator tube* in a radio set. It is the function of the detector or demodulator tube to remove or eliminate the high frequency carrier wave, leaving only the A.F. to be amplified by the A.F. amplifier. The process of eliminating the carrier wave is called demodulation or, more often, detection. With respect to the passage of a signal through a radio set, the A.F. amplifier follows the detector. From this brief description it should be clear that in one form or another every radio set has an R.F. amplifier, a detector and an A.F. amplifier. The R.F. and A.F. amplifiers may be elaborate and complex or they may consist of simple single stage amplifiers.

Since A.F. amplification is relatively simple, a study of it is desirable before taking up the study of detection or demodulation. Therefore, we

will leave the study of this general subject to a later lesson to explain, taking up the study of A.F. amplification in this lesson. With this knowledge as a background, you will be in a better position to appreciate the fine points of demodulation.

An A.F. amplifier will amplify any A.F. signal which is properly fed to it. The usual sources of A.F. signals are the output of (1) a detector tube in a radio set, (2) a microphone, (3) a phonograph pick-up unit and (4) a photocell as used with sound motion picture film. For the time being, we will not consider the last three sources of A.F. but will *confine our remarks to A.F. as it is provided by the output of a detector tube* in a radio set. Therefore, in this lesson when we refer to A.F. or a source of A.F., try to keep in mind that we are referring to the output of a detector tube as used in the average radio set.

The physical parts of an A.F. amplifier are: (1) a suitable input circuit to the first tube in the A.F. amplifier, (2) one or more radio tubes to build up the voltage and power of the signal to the desired level and (3) a suitable output circuit which will feed energy to a speaker for the production of sound waves.

There are two main aims of an A.F. amplifier. These are: (1) to build up or amplify voltage and (2) to develop power. These are distinctly not the same thing. Remember voltage is a driving force which makes current flow. The higher the voltage, the more the current that flows *if the resistance remains constant.* Power, on the other hand, is the product of voltage and current or E x I. From this, it would seem that the higher the voltage, the more power there should be in an amplifying circuit. This would be true if all resistance factors remained constant (which they do not as will be brought out later) so there is always a practical limitation to the *increase of signal voltage* or power.

In some radio sets, the detector tube feeds direct into the input of the power stage. Such sets employ power tubes (pentodes) of *high sensitivity* which take a low voltage A.F. signal and translate maximum power from it. Most radio sets, however, feed the output of the detector to the input of a voltage amplifier tube which, in turn, feeds a power tube or tubes.

There is a need for voltage amplification because the output of the average detector is too low to operate a speaker to a sufficient level to create sound waves of ordinary room volume. Then when the voltage is built up sufficiently there is a need to translate it into terms of power to operate a speaker because a speaker is essentially a motor and when a motor operates it consumes power. *A speaker, therefore, is a power-consuming device* as you will learn later on when you take up the study of speakers. The most efficient device for translating signal voltage *into signal power is a power tube.* Therefore, the usual A.F. amplifier in the average radio set will include at least one voltage amplifier tube and at least one power tube. These functions may be combined in multiple purpose tubes, but essentially separate stages are employed for each function as you will learn later on.

Your first studies of A.F. amplification will have to do with voltage amplification and then power amplification will be taken up in another lesson. The differences between the two types of amplification will be made more clear as progress is made with the study.

THE AUDIO FREQUENCY BAND

The spectrum of frequencies lying between 20 and 20,000 cycles includes the extreme limits of the A.F. band. The human ear, however, can not respond to these extreme limits. Some few persons can recognize sound down to as low as 30 or 40 cycles and some few others can hear up to perhaps from 12,000 to 14,000 cycles. The average person can hear sound waves from 100 to 10,000 cycles with greatest sensitivity of the ear being in the 1,000 to 3,000 cycle range. A good high fidelity A.F. amplifier will amplify all A.F. frequencies between 30 and 10,000 cycles to some extent. The average radio set, on the other hand, may cut off all frequencies below 80 cycles and above 5,000 cycles, and the average person will not miss these frequencies. By cutting off frequencies is meant that the amplifying circuit and speaker will not respond to the extreme limits of A.F. frequencies. The wider the A.F. band covered by an A.F. amplifier and speaker, the more complex the circuit required and the more it costs. Then, too, some designers take the viewpoint that it is needless to design a wide band amplifier when so few of the people are equipped to appreciate the tone qualities it provides. Because of the foregoing factors and for the purpose of this lesson, you may assume the A.F. band to be between about 30 and 10,000 cycles.

SOUND WAVES VERSUS A.F. VOLTAGE OR CURRENT

You should understand the difference between actual sound or air waves and A.F. voltage or current. When A.F. is fed to a speaker, its diaphragm vibrates back and forth, setting up actual but invisible *air waves* which act on our ears as sound. An A.F. voltage or current, on the other hand, is purely an electrical property for, as you know, electricity itself cannot be heard by the human ear.

Actual sound air waves cannot be amplified electrically and you cannot hear an audio frequency current or voltage. The term *audio frequency* as used in connection with voltages and currents means that their rate of change or reversal is the same as equivalent changes or reversals of vibrations causing sound.

The pitch or tone of a sound is determined by the number of times the air is compressed or rarified in producing it. Figure 1 will give you a very good conception of what is called the *audible spectrum*. This is the total possible range of frequencies *within the sensitivity of the human ear*. The standard piano keyboard in Fig. 1 is given for comparison with other sounds.

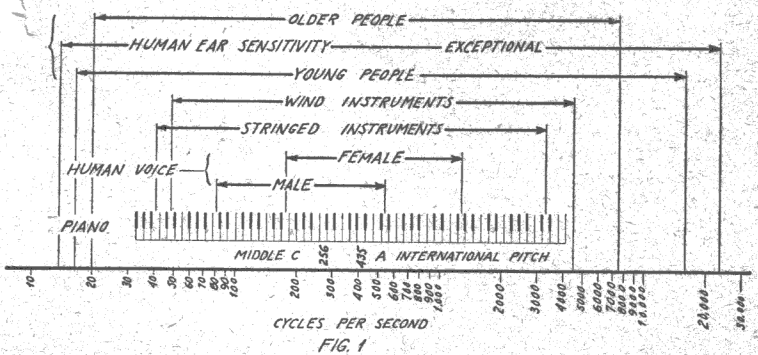


FIG. 1

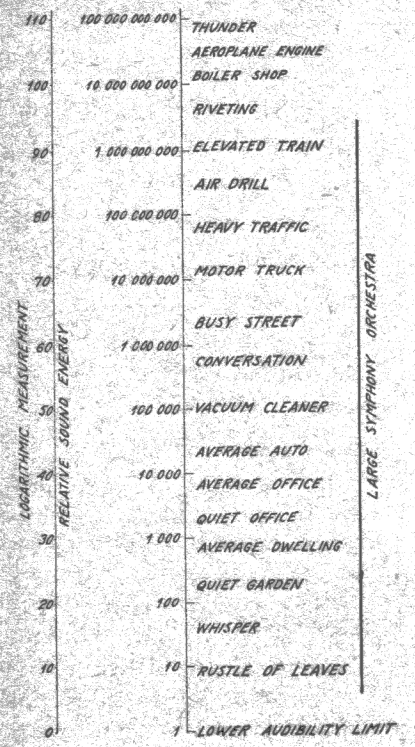


FIG. 2

Note that the average range of the human ear for all persons is approximately 30 cycles to 10,000 cycles, which is often regarded as the audio spectrum. Note also in Fig. 1 that the spectrum scale (10 to 30,000 cycles) is divided *logarithmically*, as this is the relation of one note or tone to another on the piano keyboard as on any musical instrument. It also conforms to the characteristics of the ear in tone discrimination or tone sensitivity. While musical octaves are shown in Fig. 1, an octave is the *spectrum distance* from any frequency or pitch to another of twice or one-half its value. Any note which is one octave above another (twice the frequency) is called the second harmonic of that frequency. The third harmonic is a frequency three times the value of the original or fundamental, as it is called. (The next lesson in your S.A.R. course will give more information on harmonics, octaves and fundamental frequencies.)

Figure 2 is useful in showing the sound levels you are accustomed to hearing. It is the electrical equivalents of these sound levels which must be amplified by the A.F. amplifier. Sounds vary in loudness or intensity in accordance with the energy required to produce them and the distance they travel through the air. The data given in Fig. 2 is a scale of intensities showing actual ratios of energy of sound with equivalent measurements in logarithic units which are proportional to the sensitivity of the ear. For example, you may consider the numbers of the logarithmic scale as *percentages of sound intensity*. Thus, instead of an elevated train sounding as though it produced only one tenth of the noise of a boiler shop, which is the correct energy ratio, it will sound only 90% as loud when expressed as a percentage. There is a standard unit of sound measurement called the *decibel* and abbreviated db. If you are interested in it, see your S.A.R. Math Book beginning on page 91.

As Fig. 2 shows, the human ear can adapt itself to an intensity range which is extremely large—in fact, a ratio of 100,000,000,000 to 1. A large symphony orchestra will in the course of a few seconds change the amount of its sound energy output through a ratio of more than 40,000,000 to 1 which the ear will recognize as only about 74 or 75 definite steps of detectable changes in sound intensity.

Still another property of sound by which we are able to distinguish one instrument from another or one person's voice from another is called *quality*. The quality of a sound is

determined by the shape of its wave form (its symmetry) and there are almost countless possible wave forms, as you know by experience in hearing innumerable sounds every day—more information on this in a later lesson.

From the foregoing, it is clear that a good audio amplifier should be able at least to accommodate all frequencies from 30 to 10,000 cycles; it must handle a large range of equivalent sound intensities and it must not change the wave form of the signal which it handles *as this would change the characteristic quality of the sound when reproduced.* The design of an A.F. amplifier must take all of these things into account and the repair man must ever keep these things in mind when making replacements.

GRID BIAS OR GRID VOLTAGE REQUIREMENTS

One of the most important design factors in an A.F. amplifier is provision for correct negative control grid voltage. It must be of such a value as to accommodate the expected A.C. signal swing on the grid. Too, the amount of grid bias determines the *operating point* on the Eg-Ip curve of the tube. If the grid bias is too high or too low, distortion will invariably result as will be brought out later.

To bring out these points refer to Fig. 3 which shows a basic A.F. amplifier tube having a grid bias Eg of 13.5 volts negative and a load which, for the present, will be designated as R_L. With this or a similar circuit all that is required to obtain amplification is to make the voltage Ep from plate to ground or cathode *change more than the voltage Eg, from grid to ground.* This does not specify how much direct current may flow through the plate circuit and through resistor

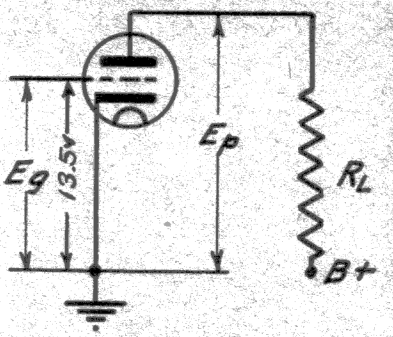


FIG. 3

R_L from B+ to ground. The facts are—about the same *voltage change* Ep would be obtained for any amount of direct current through the tube above zero and below a point called the *saturation point* where an increase in plate voltage will no longer increase plate current. An examination of an Eg-Ip curve for a typical triode tube will show if there is an advantage in more or less direct current in the plate circuit. Such a curve for a typical triode tube is shown in Fig. 4 along with other information.

HOW GRID BIAS AFFECTS THE OPERATING POINT

To illustrate the principles involved in tube operation the bias voltage of Fig. 3 may be omitted for the time being—we will assume the grid has a *zero bias.* This condition may be brought about by simply connecting the lower end of grid load resistor (Rg), which may be a coil or other type of grid load to the cathode or filament as shown in Fig. 5. Next assume a peak signal input value of 5 volts. When this is impressed on the grid it will give the grid alternate charges of 5 volts positive and 5 volts negative as indicated by the input signal wave form A in Fig. 4. Due to this type of wave form acting on the grid, the corresponding plate current

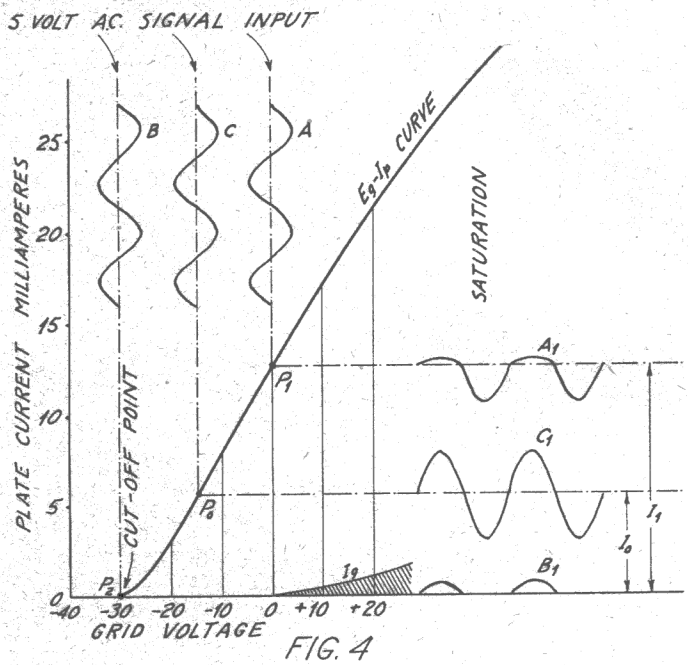


FIG. 4

wave form will be *somewhat distorted* and the plate voltage output (representing the amplified signal) will also be distorted accordingly. (A later lesson treats distortion in detail.)

When the grid swings in potential from zero to minus 5 volts, the plate current will reduce in exact proportion to the reduction in grid voltage and the plate voltage will increase in exact duplication of the grid voltage but at a greater amplitude. However, when the grid *attempts* to swing from zero to 5 volts *positive* or, in fact, as soon as the grid becomes the least bit *positive* with respect to the cathode or filament, it will attract negative electrons from the regular stream between plate and cathode and *current will flow in the external grid circuit* from grid to cathode. This, of course, is undesirable because it *robs the plate current* and creates distortion.

As represented in Fig. 6A this unwanted grid current will flow from grid to cathode through Rg, causing a voltage drop, for example, of 4 volts *making the grid negative with respect to the cathode.* Now, if 5 volts is impressed in one direction and 4 volts

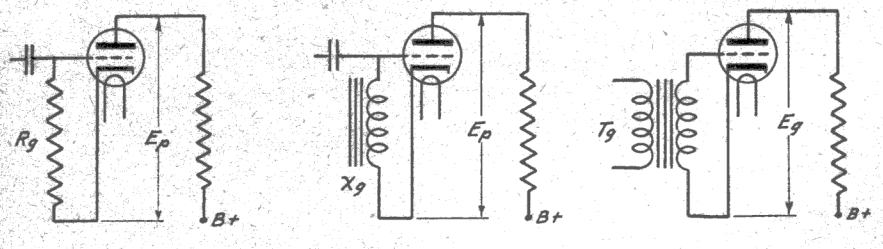


FIG. 5

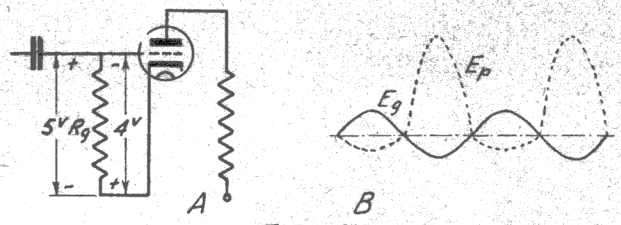


FIG. 6

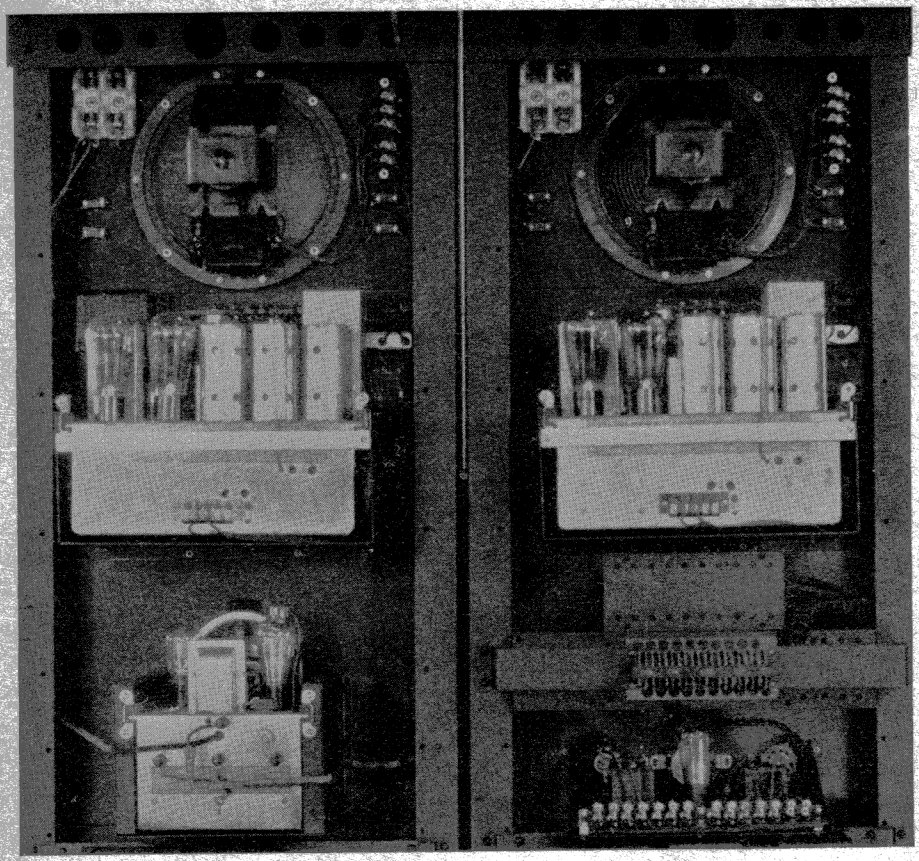
in the opposite direction, the smaller voltage will cancel a part of the larger one, leaving the *difference only acting in the circuit*. Thus, instead of the grid actually reaching 5 volts positive, it only reaches 1 volt positive (remember this is on the positive half of the signal cycle). This means that the effective grid voltage will be reduced on the positive alternation *but not on the negative alternation,* because the grid draws no current when negative with respect to the cathode.

In addition to the fact that the positive grid voltage is *suppressed* in the manner explained, when the grid is even the slightest bit positive, the grid current flow resulting will subtract from the plate current flow, thus lowering the plate current by a small amount. These two effects, grid voltage suppression, and grid current flow, both tend to prevent the plate current from rising as high on the positive grid alternation as it reduces on the negative alternation.

Naturally, if the plate current is *distorted* in this manner, the voltage from plate to cathode is also distorted *and the output voltage is, therefore, not an exact duplicate of the input voltage.* In Fig. 6B if the grid signal voltage is a perfect sine wave as shown by the solid line, the output voltage in the plate circuit will be distorted as shown by the dotted line with no bias voltage applied to the grid. The foregoing analysis shows clearly *that the grid should never be allowed to become positive under the conditions mentioned.*

There will be similar difficulty if the grid is made too negative. To show this latter effect, assume that 30 volts negative is placed on the grid of the tube in Fig. 3 by a battery. This effect is indicated in Fig. 4 by the line B which passes through the —30 volt value on the X or horizontal axis of the graph. As before, assume that an A.C. signal voltage of 5 volts peak is applied to the grid of the tube.

The 30 volt negative point along the X axis of Fig. 4 is, in this case, called the *cut-off point,* or the point on the Eg-Ip curve where the plate current will be reduced to zero by the —30 volt battery. That is, the grid voltage has been increased to such a high negative value that no appreciable electrons from the cathode can reach the plate *because the grid repels them back to the cathode.* It is obvious that any negative value of voltage *greater* than this can have no effect on the tube since the plate current will still remain zero. When the grid is swinging in the positive direction from —30 volts, a small amount of plate current starts to flow, but it takes somewhat more grid voltage to produce an increase in plate current along the lines B-B_1 (see the Eg-Ip curve of Fig. 4) than along the lines A-A_1, because the curve is not so *steep* or has less *slope* at the P_2 point where lines B and B_1 intersect.



The modern public address or theater amplifier operates on the same principle as the A.F. system in a radio set. The above view shows an A.F. amplifier system as used on board ship. *Photo Courtesy of Grace Line.*

The plate current resulting from a —30 + (+5) change of voltage (equal to —25 volts on the grid) is shown along the line B_1 in Fig. 4 and will produce a plate voltage change which is no reproduction of the grid wave shape at all. It is obvious then that it is highly desirable to operate the tube on a portion of the Eg-Ip curve (called the operating point of the tube) where changes in grid voltages will produce exactly the same type of wave form, but, of course, enlarged so as to get amplification. From the foregoing, it should be clear that if either points P_1 or P_2 are made the operating point (controlled by the application of bias voltage), the resulting plate voltage will not be a duplicate of the input voltage. Where along the curve, then, is the most desirable operating point? It is point P_o in Fig. 4, and the reasons for this will now be brought out. Note that point P_o is midway between P_1 and P_2 on the Eg-Ip curve. Points P_1 and P_2 on the Eg-Ip curve of Fig. 4 are the upper and lower limits of negative voltage for the grid bias. From this you should understand that the operating point can be shifted along the curve by changing the negative grid voltage on the tube. Curve C of Fig. 4 represents the applied signal voltage when

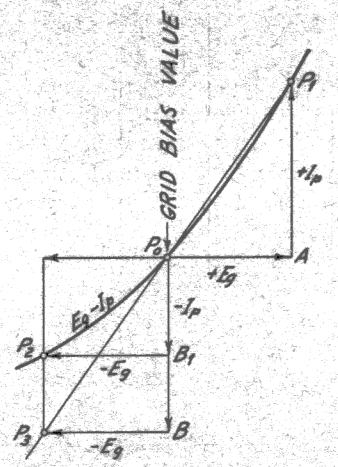


FIG. 7

the grid is maintained at 13.5 volts negative. This is applied to point P_o on the Eg-Ip curve and the same type of grid wave exists as before. Note under this condition, the corresponding plate current wave C_1 has almost identically the same or proportional shape of the input curve C. The plate voltage will likewise be closely proportional to the grid wave form except at a greater amplitude because it represents the amplified grid voltage.

Next consider the operating point P_o more closely as in Fig. 7, where a small portion of the Eg-Ip curve is purposely exaggerated for illustrating the principle involved. Note from this figure that the positive swing +Eg of the grid is equal to the negative swing —Eg. But because of the curvature of the curve the amount of plate current increase +Ip is somewhat greater than the decrease —Ip for the negative grid swing. Now, if the Eg-Ip curve were a straight line as indicated by the narrow line in Fig. 7, the quantity —Ip would equal +Ip and the plate current curve would be exactly proportional to the grid voltage wave. Triangles P_o-A-P_1 and P_3-B-P_o are identical, having their respective sides identical, but triangles P_1-A-P_o and P_o-B_1-P_2 *are not identical*, and only have one side each of equal length and these are the bases +Eg and —Eg.

From the foregoing it is quickly seen that for the *most true* reproduction of the grid voltage wave form at the plate, the section of the Eg-Ip curve over which the grid *swings* or which covers the complete grid voltage range *should be as straight as possible*. The point P_o which is approximately half way between zero grid voltage P_1, and the cut-off point, P_2, is therefore, chosen as the *operating point* of the tube. Best results for *audio amplification* are obtained when the adjustment of the negative control grid voltage makes point P_o as the operating point for the tube.

USEABLE PORTION OF THE PLATE CURRENT

It should be clear to you that the only useable part of the plate current is the varying part as steady direct current cannot be transferred through a condenser, transformer, etc. Therefore, the direct current of the tube *serves only as a medium or carrier on which is superimposed the A.F. variation.* Essentially then only enough direct current is needed to allow for sufficient variation to carry the signal. *Any additional current is wasted.*

Note in this connection that at operating point P_1, Fig. 4, a direct current of I_1 flows—90% of which is wasted. At P_2 not enough direct current flows to carry the complete signal, but at P_o enough current flows to carry the maximum variation of current and no more. In this case, curve C does not take advantage of the full grid swing, but it still is the best operating point for a maximum grid swing from zero to approximately —28 volts. This condition permits

the maximum plate current change for the amount of direct current used. The average plate current for P_o is roughly 5 ma. and the maximum is approximately 10 ma. at zero grid voltage and *zero ma. at —28 or —30 volts grid voltage.* The grid cannot be operated all the way to cut-off because of the curvature of the Eg-Ip curve near the cut-off point, for if the tube is operated near this point distortion will result. Even when the operating point is ideal as for instance at P_o in Fig. 4, a certain amount of distortion exists as will be pointed out in a later lesson.

For general conditions, then, note it is possible to swing the grid almost all the way to zero volts without any trouble due to grid current or distortion and in the other direction almost to the *cut-off point* before serious difficulty is encountered. The D.C. voltage required to maintain the grid at this average potential or *operating point* is called the *bias voltage.* For every type of tube made, the manufacturer gives the recommended voltage values which will result in operating the tube at the correct operating point on the Eg-Ip curve.

The peak voltage may be as high as the bias voltage, making the R.M.S. value .707 x the bias value. Thus, if a bias of 50 volts is specified for the grid a 50 volt peak signal may be used and this is equal to an R.M.S. voltage of .707 x 50 or 35 volts. Be sure to keep in mind that the foregoing principles apply to all amplifying tubes in general and not to just one type of tube.

HOW THE BIAS VOLTAGE IS OBTAINED

Now that you understand the need for a bias or negative control grid voltage and realize its limitations, you are ready to consider just how this voltage is obtained in a practical receiver. The way a radio set is operated determines to a large measure the method employed to obtain the bias voltage. In general, this voltage is obtained from a battery or from the voltage drop across a resistor. In the latter method, there are dozens of ways to arrange the voltage divider network of a receiver to provide the correct grid bias. The general principles of accomplishing this will be explained in the following discussion.

The simplest way to obtain bias voltage is by means of a grid battery as in Fig. 8A. It will be noted that, in effect, the plate and grid batteries are connected series adding, and that the grid battery voltage Ec is in series with the grid signal voltage Eg, which both adds to and subtracts from Ec, depending on which way the grid swings. *The peak value of Eg should never exceed the value of Ec in an audio amplifier circuit.*

The batteries may be combined as in Fig. 8B, and from this arrangement it is obvious that the circuit is the same as before, but you can see more clearly here that the plate and grid batteries form one continuous voltage. Note, however, that a *negative* voltage is applied to the grid whereas a *positive* voltage is applied to the plate. In this case, the cathode is the distinguishing point of polarity because it is common to both plate and grid.

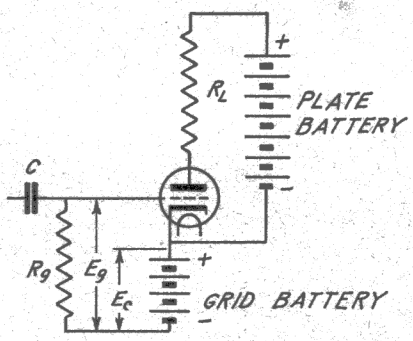


FIG. 8A

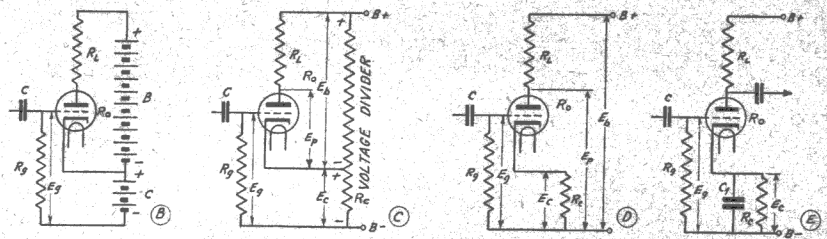


FIG. 8

It is sometimes necessary and always more convenient to get exact calculated voltages for the grid and plate. Therefore, a resistance type of voltage divider is used extensively in self-powered receivers to provide plate and bias voltage values as shown in Fig. 8C. Insofar as the voltages available are concerned, the voltage divider resistor network acts like a battery, having a large voltage drop across its extremities and other voltages proportional to the resistance at any point along the divider. The negative voltage drop across the lower section of the divider in Fig. 8C furnishes the correct bias for the grid of the tube. Note the point where the cathode of the tube connects to the resistance divider in Fig. 8C. Any voltage above this cathode connection is positive and likewise any voltage below the cathode connection is negative with respect to the cathode. Since the *grid return* of the tube connects to the most negative end of the divider, it follows that the grid itself must be negative with respect to the cathode.

Note carefully in Fig. 8C that the upper section of the resistance voltage divider across which Eb exists is connected in *parallel* with Ro (internal resistance of tube) and its load (RL). Since this part of the voltage divider serves no active function except to complete the divider circuit, it can be omitted in Fig. 8C provided that the proportioning of the internal plate resistance and load resistance with the bias section is readjusted for correct voltage on both plate and grid. The result of this rearrangement is shown in Fig. 8D. The *C* bias resistor Rc is now in the cathode circuit and its value must satisfy the relation $\frac{Rc}{Ro + RL} = \frac{Ec}{Eb - Ec}$ which simply means that in any series circuit the voltage drop across any unit is proportional to the resistance of the unit. From this, the value of the bias resistance may be found for any tube as follows:

$$Rc = \frac{Ec\ (Ro + RL)}{Eb - Ec}$$

A more convenient way to determine the value of Rc is to simply divide the voltage Ec (which it is desired to have on the grid) by the normal cathode current of the tube in amperes. In this connection, remember for a screen grid tube, the cathode current is equal to the plate current plus the screen grid current. Here is a practical example. A 6F5 or 6SF5 high-mu triode tube requires a plate voltage of 250, and at this voltage, a cathode current of .9 ma. flows. A negative grid voltage of 2 volts is required for the grid. The problem is what value of cathode resistor (connected between cathode and ground) is required to give this value of grid voltage? $R = \frac{E}{I}$, therefore, the value

of the cathode resistor is equal to:

$$R = \frac{2}{.0009} = 2222 \text{ ohms.}$$

For round figures, a value of 2000 ohms would be practical. In a like manner, other values of cathode bias resistors for other type tubes would be calculated.

CONDENSER NECESSARY TO BYPASS CATHODE RESISTOR

Because the bias resistor is connected from cathode to ground or, in some cases, to B— of the voltage divider, it carries the *plate current* of the tube and the variations of plate current (A.C.) bring about undesirable changes in grid voltage. As the grid becomes more positive or, more exactly, *less negative*, the plate current increases. This increased current must flow through Rc. *The cathode also becomes more positive than usual.* This counteracts to some extent the effect of the grid on the signal as the difference in potential between the grid and cathode cannot be as great as usual. This is the reverse of regeneration—therefore, it is called *degeneration.* The varying part of the voltage across Rc in the cathode circuit is, of course, the same signal variation that occurs in the plate circuit because the plate and cathode circuits are in series. The variation in the signal is desired in the plate circuit, *but it is undesired in the cathode circuit* for reasons already mentioned. To eliminate the cathode variations a condenser is connected in parallel to Rc. This condenser must have less A.C. *reactance* in ohms to the flow of A.C. than the resistor Rc offers in ohms. The A.C. signal always seeking the path of least resistance will, therefore, flow through the condenser and to ground, and a minimum voltage drop will occur across it. The D.C. component of the cathode current, on the other hand, cannot flow through the condenser and is forced to flow through the resistor. Thus, A.C. or the signal variation of the cathode current does not flow through the resistor, and, therefore, the negative grid voltage is disturbed a minimum with cathode variations.

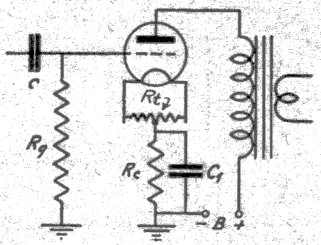


FIG. 9A

Condenser C1 in Fig. 8E maintains the voltage Ec across Rc almost constant and prevents the degenerative action mentioned in the foregoing. The value of a condenser like C1 in Fig. 8D is calculated to have minimum reactance at the frequencies involved, namely from 30 to 10,000 cycles. Refer to your lesson on condensers for reactance formulas.

There are other methods of obtaining the D.C. bias voltage such as those shown in Figs. 9A and 9B. In Fig. 9A a resistor is connected to the center tap of the filament resistor, Rt. This acts essentially the same as the one in Fig. 8E, because in this case the filament is the cathode, and the center tap resistor Rt provides a point

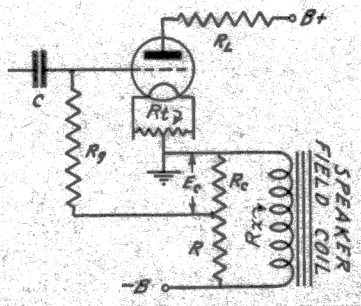


FIG. 9B

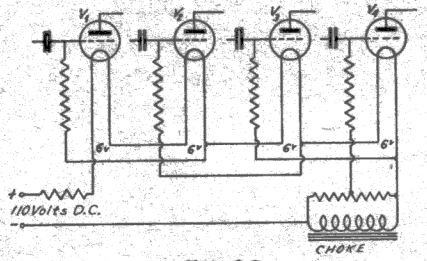


FIG. 9C

of *zero voltage* across the filament circuit resulting in minimum hum since the filament is A.C. operated. Still another method is shown in Fig. 9B where a portion of the voltage drop across a choke coil is used for bias voltage purposes. Only a small fraction of the plate current flows through the resistors R and Rc in Fig. 9B. In such a case as this, the parallel resistor formulas are used to calculate the values of R and Rc. The value of the field coil resistance Rx and the amount of plate current flowing must also be known or calculated. In this figure the values of Rc and R are so proportioned that the voltage drop across Rc will be the proper value for the grid bias of the tube.

D.C. OPERATED RECEIVERS

Where D.C. operated receivers are used the bias voltage is obtained through successive voltage drops across tube filaments (from a D.C. viewpoint a tube filament acts like any other resistance) as in Fig. 9C. While you are now studying audio amplifiers it might be well to mention that R.F. tubes are often biased in exactly the same way as has been described for A.F. amplifiers. In the case of Fig. 9C, tube V1 is biased by the voltage drop across the filament of tube V2. Trace the grid return of tube V1 and note it connects to the filament circuit of tube V2. In the case of a D.C. operated tube with a filament instead of a cathode, the bias voltage may be regarded as the voltage between the center point of the filament and the grid. If tube V1 and V2 of Fig. 9C have 6 volt filaments, the bias of V1 is 6+ ½ of 6 or 9 volts.

BIAS CELLS AND RECTIFIER BIAS CIRCUITS

A special purpose chemical voltage cell (similar to a battery) has been developed for low bias voltages which produces about 2 volts when charged with a voltage from the grid circuit and maintains this voltage for a considerable time. Such a unit is called a *bias cell*. It is usually used to bias the triode grid of such multiple purpose tubes as the 6Q7. This method is only suitable for low bias voltage values. The circuit for the bias cell is shown in Fig. 9D. Clips are usually used to hold the bias cell in place.

For extra *high bias values* where the plate current of a tube is not suitable for bias purposes a separate rectifier bias supply is used as in Fig. 9E. Since little or no current is required to maintain a bias voltage almost any tube can be used as a rectifier for a circuit like Fig. 9E.

AUDIO CIRCUIT ANALYSIS

A more complete resistance coupled audio amplifier is shown in Fig. 10

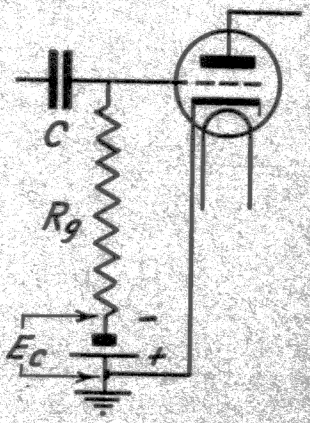


FIG. 9D

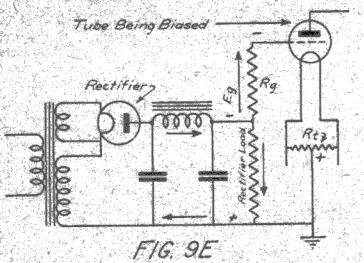


FIG. 9E

than you have studied up to now in your S.A.R. course. The *total load* in the plate circuit of tube V1 in Fig. 10 is not due to R_{L1} alone, but there are other circuits which need to be considered as well. See Fig. 10A. Through condenser C2 you can trace two circuits to ground. One of these is through the grid-cathode capacity and Rc_2 of tube V2 and the other is through Rg_2—Rg_2 is called a *grid-leak* (or grid load) because it allows a path for the signal between the grid and cathode. The name grid leak comes from the fact that the resistance allows electrons to leak off or away from the grid and so return to the cathode. Another circuit in Fig. 10 which must be considered is the one to the next stage through the grid-plate capacity of the tube V2 to C3. See Fig. 10B.

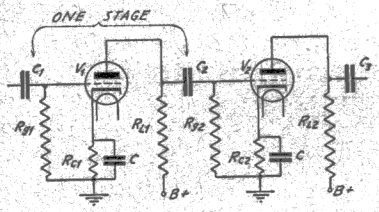


FIG. 10

All of these circuits have impedance and they shunt the plate-to-ground circuit of V1 and thus *limit* its ability to swing the voltage at the plate of V1 or to V2 a maximum amount. There is impedance naturally combined with the Rp or the internal plate resistance of tube V1 or V2.

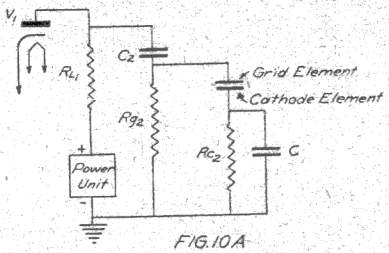


FIG. 10A

All of these impedances are in parallel, and because of this, changes of the plate resistance Rp have a *lower total effect on the voltage change at the plate.*

Now to get the voltage change at the plate of tube V1 or V2 in Fig. 10 as large as possible *all three of the impedances mentioned should be as high as possible.* However, the distribution of total voltage change across the load is divided in proportion to the impedance or reactance values encountered. Condenser C2 in Fig. 10 is in series with all three circuits and should have a low reactance (high capacity) in ohms as compared to the resistance of Rg_2 or the impedance of the grid-cathode circuit or the grid-plate circuit. All of the voltage dropped across the condenser C2 is lost and the voltage drop from grid to ground through resistance Rg_2, or to the cathode is the only useful signal voltage that can be made to act on the grid of V2. The *impedance* of the coupling condenser C2 must, there-

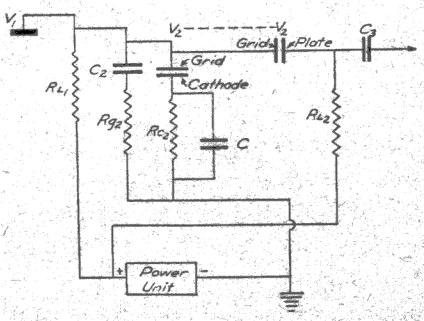
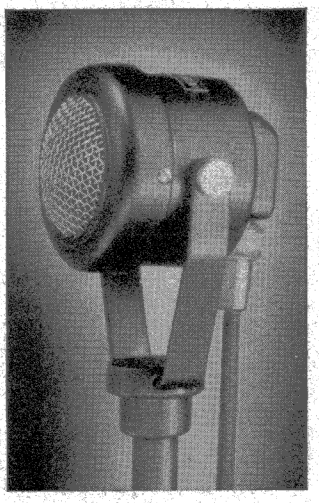


FIG. 10B



Practically all A.F. sounds as reproduced from the average radio set originate from a microphone. The above view is typical of microphones used in radio stations, public address systems, etc.

fore, be *small* (to prevent too much signal loss) as compared to all three of the other impedances, for remember they are all in parallel. The connection of impedances or resistances in parallel means the total effective Z or R will be less than any one in the group. If the total Z is made too small, little voltage drop will occur across the grid load resistor and hence minimum signal voltage will be applied to the grid of the tube. On the other hand, condensers C1, C2 and C3 of Fig. 10 cannot be too large, as their leakage may reach too high a value. Note in Fig. 10 that there is a high positive voltage applied to the left sides of C1, C2 and C3. On the right side these condensers connect to ground through grid resistor loads Rg_1, Rg_2, etc. These condensers must, therefore, be of good quality and have correct voltage rating.

VOLTAGE LOSS ACROSS COUPLING CONDENSER

Of the total signal voltage available at the plate of one tube, a percentage depending on the values of (1) *frequency* and (2) *coupling capacity* is available to act on the following grid. The percentage of Ep that is available under these two most important conditions is shown in Fig. 11. Note that the effectiveness of the circuit in passing the amplified voltage from one tube to another *increases with frequency and with value of coupling capacity.*

The graph shown in Fig. 11 is divided logarithmically so as to show the range of operation in a small space. Note there are two curves, one marked 400 cycles and the other .01 mfd. The 400 cycle curve is read with reference to the C or mfd. scale at the bottom of the graph, while the .01 mfd. curve is read with reference to the F or cycle scale. An example of using the graph follows. First, consider the 400 cycle curve. This is assumed to be a steady 400 cycle signal fed to the amplifier. For a given value of coupling condensers, such as C1, C2 and C3 in Fig. 10, so much signal energy will be passed by the condenser and so much will be lost across it. Suppose you want to know how much this will be when a .01 mfd.

This photo shows a 6J5GT tube made by *Hytron*. This tube is typical of the GT construction. The tube is of the type that may be used as a detector, oscillator or triode amplifier.

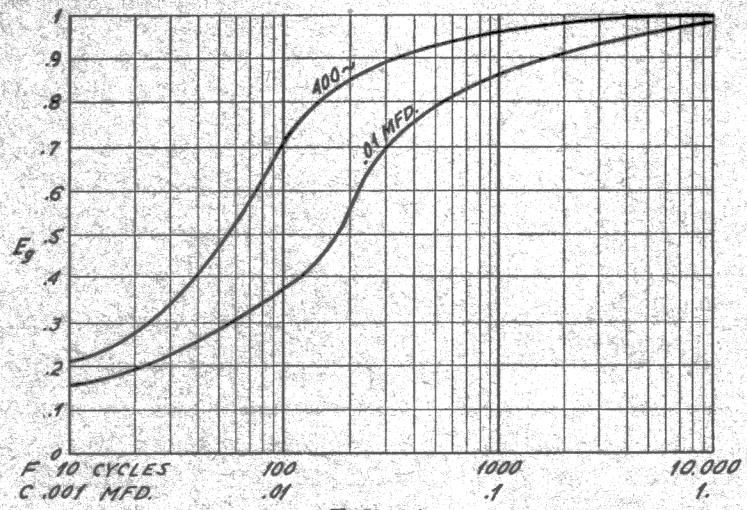


FIG. 11

coupling condenser is used. Trace up the .01 mfd. line until it intersects the 400 cycle curve. Then trace over to the left and read the percentage value on the vertical scale. Note it is .7 which is equal to 100 x .7 = 70%. Thus at 400 cycles with a coupling condenser value of .01 mfd. the amount of signal energy passed by the coupling condenser is 70% and the amount lost across it is, therefore, 30%.

Now for the .01 mfd. curve. In this case, C is assumed to be held constant at .01 mfd., and the frequency scale shows a variation of from 10 cycles to 10,000 cycles. The amount of energy transferred by the coupling condenser can, therefore, be read from the graph for any frequency between 10 and 10,000 cycles. To find out what it is at 100 cycles, trace up the 100 cycle line until it intersects the .01 mfd. curve. Then read over to the left and note the percentage value is approximately .375 or 37.5%. In this case, 100—37.5 or 62.5% of the signal energy is lost across the coupling condenser and only 37.5% is passed by the condenser. At 1,000 cycles, the amount of energy passed is 85% and only 15% is lost. In a like manner, other values can be obtained from the graph by using the proper curve and scale. In all of the foregoing, the total effective input impedance of the tube (between grid and cathode) has been assumed to be 100,000 ohms. Actually this varies to some extent with frequency. To increase the amount of voltage transfer at the lower frequencies, the coupling capacity should be as large as possible as you will note from a study of Fig. 11.

The resistors Rg_1 and Rg_2 in Fig. 10 shunt the grids to ground and should be large as compared to the grid-cathode impedance. (Note that we are in this case referring to two stages of audio amplification.) This permits the total impedance to be as high as possible which is desirable as it allows for maximum signal voltage drop to occur across it. This resistor will defeat the purpose of the amplifier if it is too high in value as the coupling condenser will not be able to discharge through it rapidly enough to follow the wave form supplied to it. No exact values can be

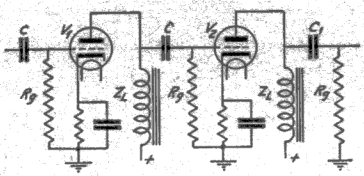


FIG. 12

stated (due to consideration for overall design) but for ordinary receiving tubes and circuits Rg_1 and Rg_2 should not exceed 2 megohms nor should they be less than ½ megohm.

PLATE CIRCUIT CONSIDERATIONS

The chief disadvantage of resistance in the plate circuit of a vacuum tube amplifier is that the actual voltage on the plate is low because of the drop in the voltage across the plate series resistor R_L, for example, such as R_{L1} and R_{L2} in Fig. 10.

A coupling system designed to overcome this difficulty makes use of iron core coils which, as you know, has a small D.C. resistance, but an extremely high A.C. reactance or impedance. The combined reactance and resistance produces a very high A.C. impedance, yet the voltage at the plate is practically the same as that at the supply source because there is no large IR drop across the plate load, R_L.

In Fig. 12 where an impedance-capacity coupled circuit is shown, the plate load impedances are marked Z_L. In other lessons we have shown how the impedance varies with frequency, but the results of shunting a plate load Z_L with a resistor for uniform amplification has not been completely explained.

The total impedance of a circuit having resistance and inductive reactance in parallel is never larger than the individual impedance of either one. This makes the problem quite simple. If R_L in Fig. 13 is about 100,000 ohms, the total plate load impedance composed of R_L and Z_L cannot exceed 100,000 ohms regardless of the value of Z_L because of the parallel law. While the impedance Z_L can decrease, it usually is such a high value that a *satisfactory load* is formed for the amplifier at frequencies down to as low as 40 cycles.

Choke coils may be used as grid loading coils, such as Zg in Fig. 14, in which case, the amplifier gives practically the same results as when using resistance loading. Here the portion of the total impedance supplied by the grid-cathode circuit increases with frequency and amplification at higher frequencies are favored more than in a resistance-capacity or impedance-capacity coupled circuit. The expense of this double or dual impedance circuit as in Fig. 14 seemed to prevent its wide application. Even with the advantages of high plate voltage it has never been preferred above the straight resistance-capacity coupled amplifier such as that shown in Fig. 10.

AUDIO TRANSFORMER COUPLING

As explained for radio frequency amplification there is a varying current flowing through the plate circuit of a tube which is capable of inducing voltage in any conductor through which its magnetic field sweeps. Thus, instead of using a varying voltage from a condenser to create a varying electric field it is just

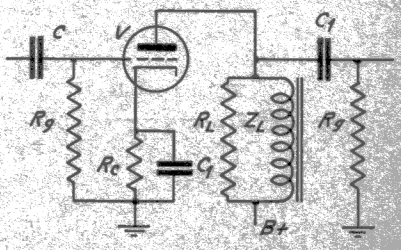
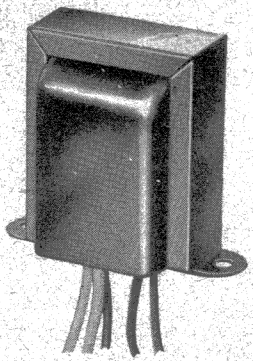


FIG. 13



The above shows a typical A.F. replacement transformer. All such transformers are similar in outside appearance, and it is only by examining the wire leads or checking a manufacturer's number that such transformers may be identified.

as easy to use a varying current to produce a varying magnetic field when coils are used.

Your former studies have indicated that a high plate load impedance was most suitable for high voltage gain. With this in mind you are ready to study the audio *iron core* transformer as a means of coupling stages and providing a load for a tube's plate circuit. The primary of the audio transformer is, of course, placed in series with the plate circuit and its A.C. *impedance* depends on the resistance of the wire used as a winding, the number of wire turns, size and arrangement of iron or core material and the amount of energy being extracted from the core by the secondary.

This may seem to be an unusual way to measure or to regard the primary impedance, but if attention is given to each of these items, accounting for the total primary impedance of an audio transformer will be remarkably easy.

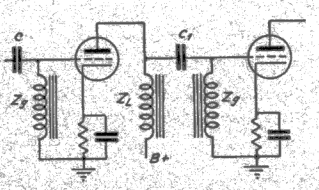


FIG. 14

The expanding magnetism in the primary sweeps through the primary and produces a reverse voltage opposing the one applied. This field also sweeps through the secondary—as well as everything in its path—and induces a voltage in it. The amount of voltage induced in the secondary is determined by the number of turns and fractions of turns in the coil. Except for losses and energy being withdrawn from the field, the self-induced primary voltage is the same as the applied voltage. The voltage in any other winding will be the voltage of the primary multiplied by the ratio of turns of this to the secondary coil. Thus, if the secondary winding has twice the turns of its primary it will have twice the primary voltage induced into it. Here, of course, we are only referring to the *voltage change across the primary* which is simply the plate voltage change due to amplification. (In a later lesson magnetic principles of the transformer core are treated in detail.)

Now, if current is drawn from the secondary by placing a resistance or impedance across it so as to form a load, the voltage drop within the winding due to this current will be opposite to that applied and the total will be reduced because for the amount of current originally flowing the magnetism has been reduced due to the secondary current flow.

As the opposing voltage is reduced the applied voltage forces more current through the primary as its reactance has been lowered. Conditions at the secondary through mutual inductance of the primary and secondary are instantly made effective in the primary and the primary impedance depends much *more on the secondary load* than anything else. When the secondary is open (not connected to a load) the primary impedance is

extremely high and when the secondary is shorted, the primary impedance is only a very few ohms.

AUDIO TRANSFORMER CONSIDERATIONS

There are several practical concepts about audio transformers and their behavior which tell the entire story of their operation and should be definitely fixed in mind. *The amount of current that the primary will take* from any A.C. voltage source *is proportional to the secondary current.* The secondary load determines the secondary current which *automatically regulates the primary current.* The *impedance of the primary* or of any transformer winding is, therefore, *not a definite value.* When an impedance value is given the loading of the other winding or windings must be specified as well as the frequency.

For a given amount of iron core material, a certain minimum number of turns of wire for each volt applied are necessary to permit the primary current to be converted into magnetism and to induce voltage into one or more secondaries. The factor *turns-per-volt* is the same for every winding of a transformer, and is low for high power transformers and high for low power transformers. This determines all of the voltages of the transformer and the ratio of one voltage to another. If the secondary has a higher voltage (more turns) than the primary of the transformer it is called a *step-up transformer,* and if it is lower, it is called a *step-down transformer.* This is a matter of connection rather than design as the primary is simply the winding arbitrarily chosen for the power source. The remaining winding must be the secondary. For other requirements, the secondary could become the primary if that was desirable.

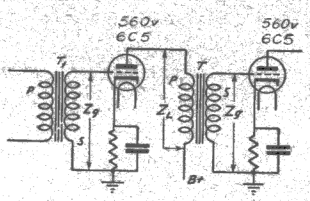


FIG. 15

When one winding has an impedance established with the use of a definite load, the ratio of impedance values will be proportional *to the square of the turns ratio or voltage ratio.*

Considering the use of a type 56 or 6C5 tube, which are two of the most commonly used low power audio amplifiers (Fig. 15), the A.C. plate resistance of these tubes is approximately 9500 ohms. The primary impedance of an A.F. transformer for these types of tubes should be somewhat greater than this figure so that the greatest possible voltage gain may be had. If the transformer has a step-up ratio of 3 to 1 or 3 times as many turns in the winding used as the secondary as in the primary, it will have 9 times the impedance—the square of *turns ratio* gives the secondary impedance. If the secondary is loaded with a resistance of 85,500 ohms, the primary will have an impedance of 9,500 ohms. The former is 9 times the latter which is the impedance ratio. If this 85,500 ohms secondary resistance value is increased, the primary impedance will increase accordingly.

Under load, the secondary becomes a new source of power and *its voltage reduces with an increased load.* Although this tendency is always true, a well designed transformer will show least change in voltage for a given load change.

The flow of current brings about magnetism and when this is in air or in any non-magnetic substance, it

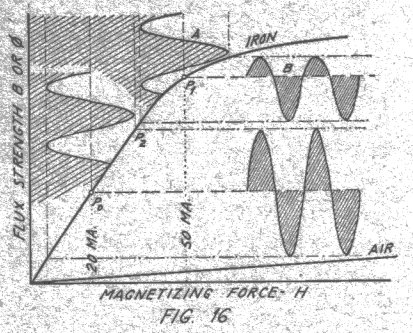


FIG. 16

is always directly proportional to the current producing it. Iron does not work in exactly this way, however, and the actual magnetic field or flux in the iron core is proportional to the current intensity through its windings only for relatively small currents. As the current increases, the magnetism or flux strength increases up to a definite current level and then for additional current, the magnetism does not increase quite so much. The curves in Fig. 16 bring out this principle in detail. Above 100 milliamperes for this case very little additional magnetism can be obtained from an A.F. transformer for an increase in current. Now, if the average plate current of a tube is 50 ma. and a signal on the grid makes it change from 40 to 60 ma., curve A, the magnetism would vary as curve B which, as you will note, is considerably distorted because the half cycles of the wave form are not the same. This magnetic wave form would determine the wave shape of the voltage induced in the secondary as it is the varying magnetism which is responsible for the voltage.

If the tube is biased so that it will allow only 20 ma. average of current through it, it will operate nicely at point P_o instead of P_1 in Fig. 16. Note with P_o as the operating point, the wave shape of the secondary voltage is symmetrical whereas it is not symmetrical at B because of core saturation. It is not always possible to tell at what point on its *magnetization curve* a transformer is operating, and there is definite danger of serious distortion due to *saturation* of the core of the transformer. One way to insure that this trouble is eliminated is to prevent the direct current of the plate circuit from flowing through the primary of the transformer. How then can the tube plate circuit be completed if plate current is not to flow through the primary? See Fig. 17 as to how this is accomplished.

In Fig. 17, condenser C carries over the voltage variations from the plate

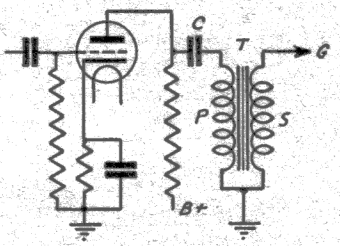


FIG. 17

circuit to the transformer's primary P by charging at a higher voltage level and discharging at a lower level. In Fig. 16 the current through the primary can reach approximately 35 ma. (P_2) in either direction, without any distortion. While any transformer can be overloaded, this one (Fig. 17) can carry about 5 times the signal current when *shunt coupled* as when series coupled, as in Fig. 15.

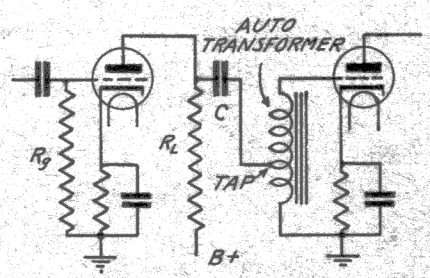


FIG. 18

Another A.F. transformer coupling method is known as auto-transformer coupling. This method permits a slight saving in wire and weight. Figure 18 shows the circuit. It is so called because part of the winding is used for the primary (the lower part in this case) and the entire winding is the secondary. This kind of transformer must be connected as shown, because no direct connection can be made with the plate of one tube and the grid of the next without special circuits. The turns-per-volt value is uniform throughout the entire transformer and hence the step-up ratio is in this case equal to the total number of turns divided by the number in the lower section. If a total winding is assumed, for example, of 750 turns with 250 from the tap to the lower end, the voltage step-up ratio would be $\frac{750}{250}$ which is 3.

To by-pass some of the direct current out of the primary and make the impedance-frequency characteristics more favorable, a resistance is very often shunted across the primary or secondary of the transformer. Although the effect is identical if this is done to either the primary or secondary, there is a slight advantage in shunting the primary as it reduces the D.C. through the winding. If the transformer is a 2 to 1 step-up type, it will require 4 times the resistance across the secondary as across the primary for a given effect.

Still another method of A.F. transformer coupling is known as impedance-capacity coupling as shown in

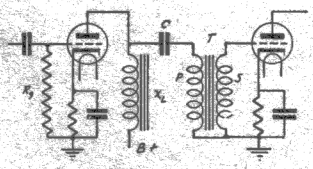
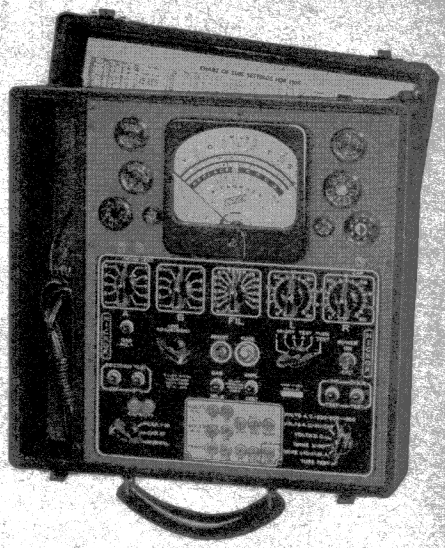


FIG. 19



It is essential that radio tubes be tested at frequent intervals. The above view shows a manufactured tube tester. Tubes should be tested by this or a similar method such as substituting tubes known to be in good condition for those of doubtful condition and then noting the results as per the performance of the radio set.

Fig. 19. This method of coupling is similar to the others which have already been mentioned. The winding in the plate circuit of the tube to the left is an iron core A.F. choke coil. Signal variations across it cause a signal voltage drop as usual and the signal is passed on to the transformer T by way of coupling condenser C. The circuit action is very similar to that of Fig. 17. Since in Fig. 19 a wire winding is used for the plate load little D.C. voltage drop occurs across it, and, therefore, it requires less D.C. voltage for its operation than does the circuit of Fig. 17. Otherwise there is little to choose from between these two types of circuits.

SCREEN AND SUPPRESSOR GRIDS

The advantages of tetrode and pentode (screen and suppressor grids) tubes in connection with R.F. amplifiers may also be applied to audio amplifiers. Best application may be utilized in resistance-capacity coupled

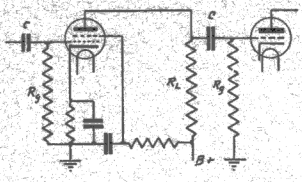


FIG. 20A

amplifiers as in Fig. 20A and Fig. 20B, showing a tetrode and pentode circuit. It is not necessary to be concerned about internal tube electrode capacities at A.F. because the circuits are untuned and the frequencies are so low that no serious trouble due to capacity between tube elements can exist. The advantages lie in high gain and large plate voltage swing in the case of the pentode where *secondary emission* is avoided.

DIRECT COUPLING

There are several methods of directly coupling the plate of one tube and the grid of the next *so that no reactance either capacitive or inductive is present.* This method is called *direct coupling* but has been used little in the past. A description is included in this lesson for completeness of A.F. circuits. By this time you have had enough instruction about potentials and polarity to understand this type of coupling quite clearly from the following description.

We will start with two tubes, a 58 and 2A3 and show how they may be directly coupled. Following are listed the voltages which must be applied to each tube electrode and the plate and screen currents required for normal operation.

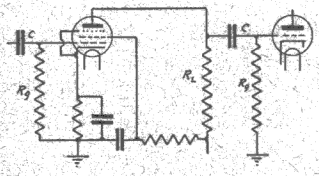


FIG. 20B

	Eb	Ec	Esg	Ip	Isg
58	250	—3	100	8.2	2.0
2A3	250	—45	.....	60	.....

To have direct coupling, the *plate of the 58 tube must connect directly to the grid of the 2A3 power tube.* This is shown in Fig. 21A. Starting at the lowest potential of the complete amplifier which is the control grid of the 58 tube, the return of the grid load Rg, .5 megohm must connect to the lower end of a large voltage divider *from which any voltage desired* may be selected. This is shown in Fig. 21B. Next at Fig. 21C, the 58 cathode must connect to the divider at +3 volts so that the grid will have the proper 3 volts bias on it

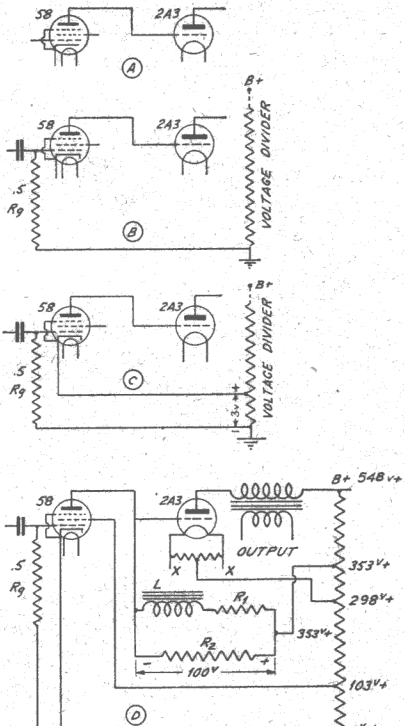
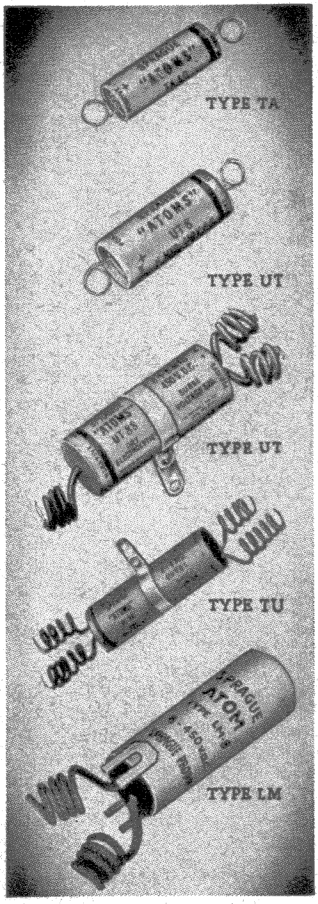


FIG. 21

through Rg. The screen of the 58 tube must be at +103 volts or 100 volts above the cathode potential and is connected to the voltage divider as



As you know from your previous studies, condensers are used for many purposes in radio. The above photo shows five types of condensers which are regularly used for radio replacement work.

in Fig. 21D. To the 58 plate and 2A3 grid must be connected a circuit which has a resistance of $\frac{100v}{.0082\ ma.}$ or 12,200 ohms so that it can carry exactly 8.2 ma. at 100 volts. It is attached to the voltage divider exactly 100 volts higher than is required at the 58 plate or at 353 volts. With a very high inductance L and with the right combination of values for R1 and R2 exactly 12,200 ohms D.C. resistance may be obtained. This provides a very high A.C. impedance with good impedance-frequency characteristics.

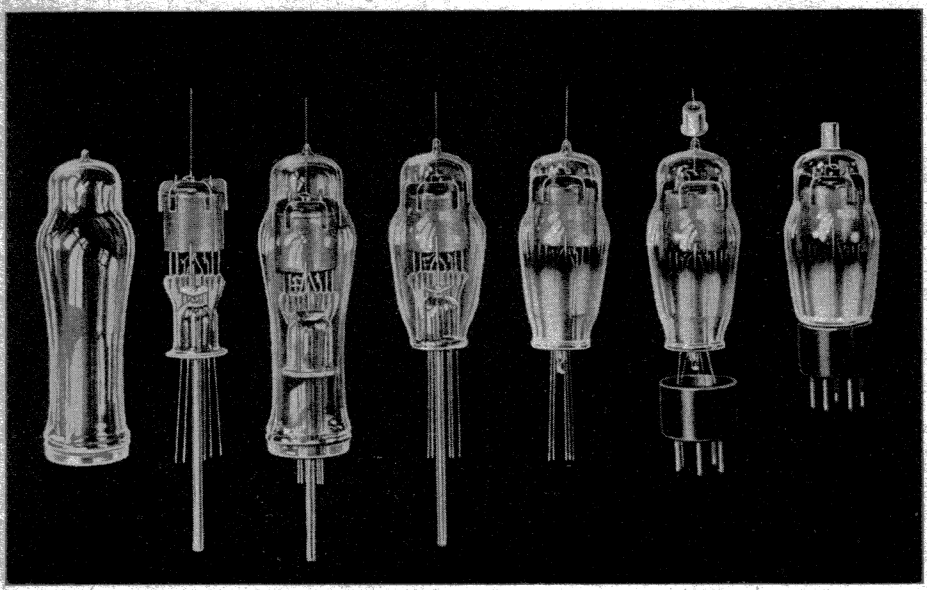
Now the 2A3 filament (this tube has no separate cathode) must be 45 volts higher than the grid which is at +253 volts, so the filament at the 2A3 tube is connected to +253 +45 = +298 volts on the divider. The plate voltage of the 2A3 tube must be 250 volts above that of the filament, so it is connected through the transformer primary to a point +298 +250 = +548 volts on the voltage divider. With this arrangement each of the tubes are operated with correct and specified voltages and variations of the 58 plate also act on the 2A3 grid as the two are directly connected.

The great disadvantage of this type of A.F. amplifier is the high voltage required to operate it and the fact that varying tube characteristics sometimes upset the operating potentials.

THE POWER AMPLIFIER

Up to this point, we have simply considered how a varying voltage or a voltage change may be amplified. Voltages alone can not be used to operate a speaker, but it can be used to force current to flow and from this power may be obtained. Of two amplifiers having the same voltage gain, the one which can *maintain its output voltage* across the lowest impedance is the best power amplifier because power equals $\frac{E^2}{R}$. The tube which maintains the highest current through the highest resistance also has the most power. Likewise the one which maintains the highest voltage at the highest current is the best power amplifier.

A certain average plate current will flow in a tube when it is put into operation. This multiplied by the voltage from plate to cathode will give the power being dissipated within the tube. Since all of this power turns to *heat* and the plate surrounds all



The above view shows the several stages of construction of the glass type vacuum tube. At the left is shown the glass envelope and electrode assembly—the finished product is shown at the right. *Courtesy of RCA.*

elements, the plate electrode must radiate or dissipate it—thus the heat so generated is often called *plate dissipation* and is measured in watts.

When the plate circuit includes an *external load* it, too, dissipates energy in heat or in other forms in accordance with the relation I^2R or $\frac{E^2}{R}$, etc. For example, if the voltage is changed 100 volts R.M.S. on the plate and the impedance is 200 ohms, power will equal $P = \frac{E^2}{R}$ which is $\frac{100^2}{200} = \frac{10{,}000}{200} = 50$ watts. The direct current power in this case is simply converted into A.C. power. In this a portion of the power already in the plate circuit is simply changed to a more useful form.

You have seen that for maximum voltage amplification the plate load must be made as high as possible in practical work. This does not mean that the maximum amount of power is available, as the power reduces with an increase in the load R or Z because

$$\text{power} = \frac{E^2}{R} \text{ or } \frac{E^2}{Z}.$$

It is desirable to know how the *external plate load impedance* should compare with the *internal tube or source impedance* for maximum power to be extracted from the tube. The total impedance of the entire plate circuit is $Rp + R_L$. Also the voltage change at the plate is the same thing as having an A.C. generator at the plate terminal.

To reduce a power amplifier circuit to the simplest possible form, a circuit like that of Fig. 22 may be employed. The current in this circuit will be equal to the voltage divided by the total resistance or:

$$I = \frac{E}{Rp + R_L}$$

The power which R_L actually dissipates will be equal to I^2R_L and hence substituting $\frac{E}{Rp + R_L}$ for I in I^2R_L the problem becomes:

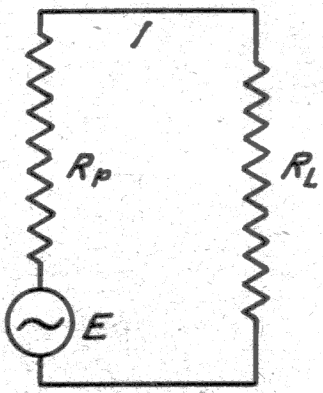


FIG. 22

$$P = \frac{(E)^2}{(Rp + R_L)} \times R_L \text{ or}$$

$$P = \frac{E^2 R_L}{(Rp + R_L)^2}$$

which may be expanded to:

$$P = \frac{E^2 R_L}{Rp^2 + 2RpR_L + R_L^2}$$

Although this formula is not as handy as others you have worked with, it is reduced to its simplest possible form. By means of it, it is possible to show what value of R_L will permit a tube to generate maximum power in an output A.F. stage. Values of E and Rp and various values of R_L may be chosen and the results may be plotted in graph form to show the amount of power consumed by R_L.

Enough values for R_L have been chosen in the following examples to give you a definite and detailed idea of the manner in which the output power varies with the value of the external plate load. These values are:

$R_L =$ 1 ohm
$R_L =$ 10 "
$R_L =$ 50 "
$R_L =$ 100 "
$R_L =$ 500 "
$R_L =$ 1,000 "
$R_L =$ 10,000 "

A value of 10 volts has been chosen for E and 100 ohms for Rp. Remember, however, these are not all practical working values but they will serve to show the principles involved. Following are the seven solutions for the power developed across R_L. Also the total current for each value of R_L is given.

$R_L = 1$ ohm.

$$P = \frac{100 \times 1}{100 \times 100 + 2 \times 100 \times 1 + 1 \times 1}$$

$$= \frac{100}{10201} = .0098 \text{ watts and I}$$

$= .0991$ amp.

If the same formula is employed it will give the following power values in watts for the other R_L values under consideration. Thus:

$R_L = 10$ ohms and P = .082 watts and I = .0908 amp.
$R_L = 50$ ohms and P = .22 watts and I = .0666 amp.
$R_L = 100$ ohms and P = .25 watts and I = .05 amp.
$R_L = 500$ ohms and P = .139 watts I = .0166 amp.
$R_L = 1{,}000$ ohms and P = .0826 watts I = .0091 amp.
$R_L = 10{,}000$ ohms, P = .0098 watts I = .00099 amp.

The number of *watts* resulting from each of these solutions have been converted into *milliwatts* and plotted with reference to each value of R_L in Fig. 23. You will note that the milliwatt curve reaches a *maximum* of 250 when $R_L = 100$ ohms and take note, too, that this is also the value of Rp. Therefore, from this you can see that any value of R_L either less than Rp or greater than Rp indicates that R_L carries less power. The current through the circuit in milliamperes is plotted in Fig. 23 so that it may be compared to the power curve. The current, of course, decreases as the external load increases. But remember power equals current times volt-

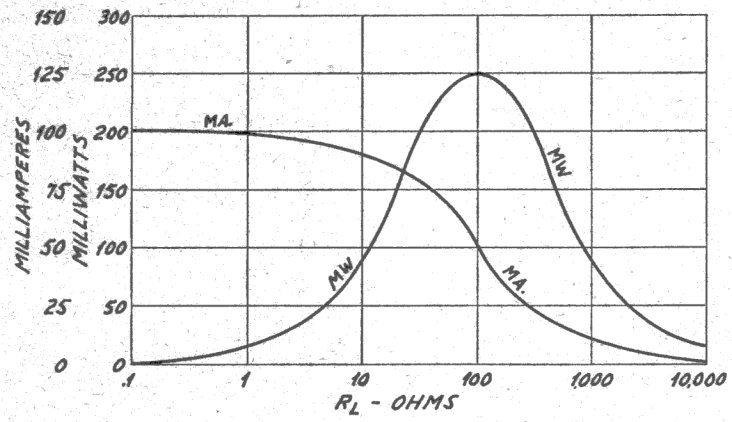


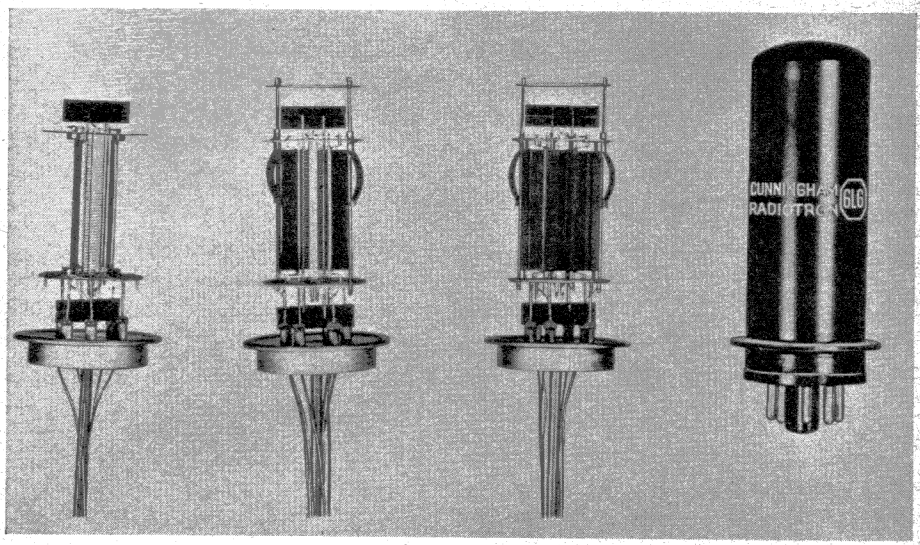
FIG. 23

age and it is at a R_L load of 100 ohms when the maximum voltage drop occurs across R_L and this value multiplied by the current flowing for these conditions gives the maximum value of power developed across R_L. This is the maximum power without regard to distortion. Since a certain amount of distortion is always present it may be necessary to increase the value of R_L above that of Rp to get maximum *undistorted* output as will be pointed out in a later lesson. If you are interested in the E values for power output calculations just remember $P = E \times I$, and therefore, $E = \frac{P}{I}$.

As you have studied before, the resistance partly determines the power in a circuit directly by I^2R or $\frac{E^2}{R}$ or indirectly by EI where resistance apportions the voltage in such a way as to affect the power. Although the current is low for values of R_L above 100 ohms in Fig. 22 the resistance is high, again forming voltage and current combinations with increasingly less power as R_L is increased in value. All of the foregoing, therefore, proves that when R_L equals Rp the maximum power (including distortion) occurs across R_L.

While this is only one case, it may be shown that this same principle holds true for any value of Rp and for any voltage value. That is, when R_L is equal to Rp regardless of the value of Rp, the transfer of power from the generator (the tube) to the load R_L will be *maximum.*

A vacuum tube and its plate load are in series and the change in plate voltage with respect to the cathode makes it act as an A.C. generator when a signal is supplied to the grid. As a generator its internal resistance Rp is its A.C. plate resistance or the plate voltage change divided by the plate current change. When the load R_L is equal to this, a maximum amount of power in the plate circuit will be transferred to the load which is exactly what we want to occur in the output stage of a radio set. From this it should be clear to you that when this is true there will be the same amount of power consumed internally by the tube as externally by the load since it has the same resistance and carries identically the same amount of current. The power consumed by the tube, however, is lost as heat. It



The construction of metal type tubes is similar to that of glass construction. The various electrodes or elements are first assembled and then sealed within a metal envelope as shown in the above view. *Photo Courtesy of RCA.*

collects on the plate and is radiated from it. The power that is continually discharged from the plate of a tube is called its plate dissipation. Not only is this power lost due to I^2R loss in the cathode-plate path within the tube, but to this is added heat due to electron bombardment, from hot cathode, metallic resistance of the plate electrode and other minor causes.

Thus in its ability to convert the D.C. power supplied to it into the A.C. power for a speaker, the power output tube cannot be more than 50% efficient under the conditions as given.

The chief difference between a voltage amplifier and a power amplifier is the impedance of its load. For a *voltage amplifier* R_L should be as high as it is practical to make it and for a *power amplifier* it should be exactly equal to the A.C. plate resistance of the tube to which it is coupled. Increasing R_L will however reduce distortion. Thus the undistorted output of a tube is always less than its maximum power output. A later lesson will treat this subject in more detail. Since the grid of either type of amplifier (voltage or power) draws no current, the only power required to supply the grid is to charge the capacity formed by the grid and cathode. Voltage amplifiers have a high voltage output with little power and power amplifiers should have a power output (formed by maximum values of current and voltage) as high as possible. A power amplifier is only needed in the last amplifier stage of a receiver, since the need in this case is to supply power to operate a speaker.

The ability of a tube to convert the plate power into useful output signal power by means of a grid signal voltage is called its *power sensitivity*. For triodes, this is low, but for pentodes, the same grid signal can bring about considerably more power output and in some cases more distortion.

The voltage gain of a voltage amplifier is usually within 80 to 90%

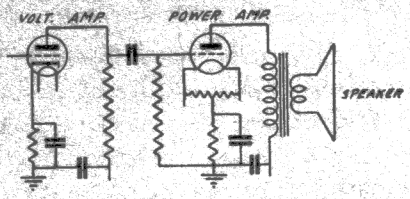


FIG. 24

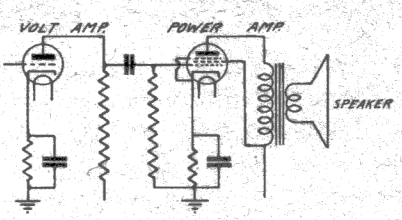


FIG. 25

of the amplification factor of the tube used, while that of a power amplifier is half or less. In the case of a pentode, it is considerably less.

In Figs. 24 and 25 are shown typical power amplifier circuits, each preceded by voltage amplifiers. Note that in the pentode tube (Fig. 25), the suppressor grid (next to the plate) is connected to the cathode and that the screen grid (between suppressor and control grid) is supplied directly from the positive high voltage. Power pentodes are constructed so that the full voltage required for the plate may also be used on the screen.

There is an outstanding difference in the load requirements for pentodes as compared to voltage amplifiers or power amplifiers. The specifications as to the *ratio* of load to R_L holds just as well as for the triode, but the characteristic operation of the pentode *will not permit* the use of a load equal to the plate resistance. You will remember it was mentioned in a former lesson about R.F. pentodes that the addition of the suppressor grid increased considerably the A.C. plate resistance of the tube. *This is just as true for A.F. power tubes of the pentode type.* The amplification factor is so high for the pentode tube that should it be provided with a load equal to the Rp of the tube, it would overload the tube with a 2 volt signal on the grid and much distortion would result.

Much less than in the case of R.F. amplifiers can distortion be tolerated in an audio amplifier. Therefore, to use the pentode as an output power tube, its distortion must be kept to a minimum. Whereas the grid and plate voltage swing for the pentode power tube are both limited for high impedance loads within the boundaries of negligible distortion, the load R_L should be reduced to only 6 or 7% of the Rp plate resistance for best results.

Obviously this lowers the operating Rp, the Mu and the distortion. It also lowers the power sensitivity of the tube as well, but is the only practical alternative to produce maximum undistorted power output.

In this lesson we have mainly considered audio amplifier principles. In a later lesson you will be shown the practical use of these principles in complete radio receivers. The principles of this lesson should be remembered, and as you make progress with more advanced lessons, you should refer back to this lesson as the need for it develops.

These questions are designed to test your knowledge of this lesson. Read them over first to see if you can answer them. If you feel confident that you can, then write out your answers, numbering them to correspond to the questions. If you are not confident that you can answer the questions, re-study the lesson one or more times before writing out your answers. Be sure to answer every question, for if you fail to answer a question, it will reduce your grade on this lesson. When all questions have been answered mail them to us for grading.

QUESTIONS

No. 1. What are the three properties of an A.F. signal which an amplifier must reproduce faithfully?

No. 2. Describe the grid voltage—plate current characteristics (Eg-Ip curve) of a good audio amplifier.

No. 3. What is the result if the operating point of an amplifier tube is too low or too high on the Eg-Ip curve?

No. 4. What will happen to an A.F. amplifier tube if the cathode bias resistor is not adequately by-passed with a condenser?

No. 5. Should the external plate load impedance of a pentode audio amplifier tube be equal to its internal A.C. plate resistance for maximum undistorted output?

No. 6. Does the impedance of the primary of an A.F. transformer depend entirely on the primary itself—explain?

No. 7. What is the main advantage of shunt coupling an A.F. transformer?

No. 8. How does an auto-transformer differ from an ordinary A.F. transformer with two windings?

No. 9. What percentage of a tube's total plate circuit power is carried by the external load R_L when the tube is delivering maximum power to a load?

No. 10. What is the chief difference between a voltage amplifier and a power output amplifier?